431-0129A

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED
Final Report

4. TITLE AND SUBTITLE
HTS Josephson E-Beam Technology with applications to RSFQ concept demonstrations in High-Tc superconductors

5. FUNDING NUMBERS

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
State University of New York at Stony Brook
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
4555 Overlook Ave., SW
Washington, DC 20375-5326

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

19960621 045

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release; Distribution Unlimited

12b. DISTRIBUTION CODE

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We have successfully fabricated and tested the first All-High-Tc circuit of the Rapid-Single-Flux-Quantum (RSFQ) logic family using a single-layer $YBa_2Cu_3O_{7-x}$ thin-film structure with 14 in-plane Josephson junctions formed by direct electron beam writing. The circuit includes two DC/SFQ converters, two Josephson transmission lines, a complete RS SFQ flip-flop, and an SFQ/DC converter (readout SQUID). Low-frequency testing has shown that the dc-current-biased circuit operates correctly and reliably at T-30 K, a few degrees below the effective critical temperature of the junctions. We have also made and studied the first SQUIDs on silicon substrates using the same method to demonstrate the feasibility of integrating HTS with silicon-based technology.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

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HTS Josephson E-Beam Technology with applications to RSFQ concept demonstration in High - T_c superconductors

FINAL REPORT

Sponsoring Organization:
Office of Naval Research

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UNCLASSIFIED

per Martin Nisenoff
Code 6850 7/8/96

431-0129A

N00014-94-1-G026

Mach 22, 1996

Table of content

Abstract

We have successfully fabricated and tested the first All-High-Tc circuit of the Rapid Single-Flux-Quantum (RSFQ) logic family using a single-layer $YBa_2Cu_3O_{7-x}$ thin-film structure with 14 in-plane Josephson junctions formed by direct electron beam writing. The circuit includes two DC/SFQ converters, two Josephson transmission lines, a complete RS SFQ flip-flop, and an SFQ/DC converter (readout SQUID). Low-frequency testing has shown that the dc-current-biased circuit operates correctly and reliably at T~30 K, a few degrees below the effective critical temperature of the junctions. We have also made and studied the first SQUIDs on silicon substrates using the same method to demonstrate the feasibility of integrating HTS with silicon-based technology.

1a. Program main objectives

- Design, fabricate and test several simple RSFQ circuits, including most of the basic components of any RSFQ logic circuit.
- Measure the thermally induced error rate and parameter margins.
- Develop and optimize software for 2-D and 3-D modeling of circuit parameters, such as inductance, critical currents and operating temperature.
- Conclude on the applicability of the HTS technology in general and e-beam writing method in particular to the RSFQ logic circuits at higher operating temperatures.

1b. Summary of Accomplishments

- Using electron-beam writing method we demonstrated the first HTS Rapid Single Flux Quantum (RSFQ) device working at ~ 30 K including such basic components as DC/SFQ converter, SFQ/DC converter, Josephson transmission line, RS Flip-Flop.
- We have measured error rates and parameter margins at operating temperature and estimated requirements for the circuit to operate at ~ 77 K.
- We have optimized and applied a new numerical modeling technique allowing us to calculate geometrical and kinetic inductance in any planar geometry used for RSFQ HTS devices
- We have successfully demonstrated the world first electron beam modified Josephson junctions and SQUIDs from YBCO films deposited on silicon substrates.

2. Introduction

2a. Identification and Significance of the Problem

2.a. HTS RSFQ logic

The past few years have witnessed rapid development of superconductor digital circuits of the Rapid Single-Flux-Quantum (RSFQ) logic family. These circuits, using overdamped Josephson junctions as active elements, store binary information in the form of single quanta of magnetic flux, $\Phi_0=h/2e\approx2\times10^{-15}$ Wb, while transferring and processing it in the form of picosecond SFQ pulses with the quantized area $\int V(t)dt=\Phi_0\approx2\text{mV}\times\text{ps}$ (for reviews, see Refs.1). The main advantage of this new digital technology is its unparalleled speed (fundamentally limited only by the superconductor energy gap) combined with very low power consumption and dc power supply. The main problem preventing practical application of the RSFQ circuits is the necessity of deep refrigeration.

This drawback could be substantially alleviated by using high-T_c superconductors which may allow operation of RSFQ circuits at liquid nitrogen temperatures [1-3]. Most Josephson junctions of high-T_c superconductors are intrinsically overdamped (and as a result have non-hysteretic dc I-V curves), making implementation of RSFQ circuits very natural. That is why considerable efforts to produce high-T_c RSFQ circuits have recently been made by several groups, although the available Josephson junction fabrication technologies are not yet mature. The Chalmers group have demonstrated [2] a circuit consisting of a truncated RS SFQ flip-flop (without the buffer junction in the reset channel) complemented by the necessary input and output circuits, using grain boundary

junctions in a $YBa_2Cu_3O_{7-x}$ thin film. The use of a low-T_c (lead-alloy) ground plane, though, has limited the circuit operation to helium temperatures. Recently the Westinghouse group have demonstrated [3] operation at 65 K of another circuit, designed as a two-stage SFQ shift register. This $YBa_2Cu_3O_{7-x}$ thin-film circuit had large inductances of the register loops, and operation of only one cell (essentially, a multi-stable dc SQUID) has been demonstrated [4]. We have demonstrated operation of a more complex all-high-T_c circuit, almost similar in schematics to that studied in Ref. 2, including all the basic elements of RSFQ logic.

2.b. RSFQ logic design and silicon technology

In many potential HTS application one would prefer to use HTS devices for some specific critical high speed functions (such as RSFQ logic) but to use conventional silicon and III-V semiconductors for other purposes. This is why it is imperative to develop *monolithic* technology capable of integrating silicon technology with High Temperature Superconductivity. Such a technology will have significantly lower cost, the substrates will have better dielectric properties than metal oxide substrates, they will also be transparent from infrared to microwave frequencies and integrable with both silicon, and HTS components. We have demonstrated feasibility of using this technology for Josephson junctions and SQUIDs made by electron beam writing and are now ready to transfer our successfully implemented RSFQ circuits from metal oxide to silicon substrates.

3. Technical Background

3.a. YBCO film preparation

3.a.1. YBCO films on lanthanum aluminate

YBCO films on lanthanum aluminate were prepared at AT@T Bell Labs using post-annealing technique. The films were quite uniform in terms of electrical properties (Tc ~89.4 K, critical current density at 77 K Jc~$5x10^6$ A/cm^2. The most serious problem suffered by this technology is the existence of inclusions of different phases which effect the overall morphology, increase kinetic inductance of the film and eventually may hurt the uniformity of the junctions.

3.a.2. YBCO films on silicon

A process for growing high quality epitaxial HTS films on buffer layers on silicon has been developed recently. The film was fabricated in Advanced Fuel Research by pulsed layer deposition technique with the buffer layer of yttrium-stabilized zirconia (YSZ). The typical cross section transmission electron micrograph of the film on silicon substrate is shown in Fig. 1. The film has high crystallographic and electronic quality approaching the quality of the film made on a regular substrate such as lanthanum aluminate and (in our case) is even superior in terms of the surface morphology.

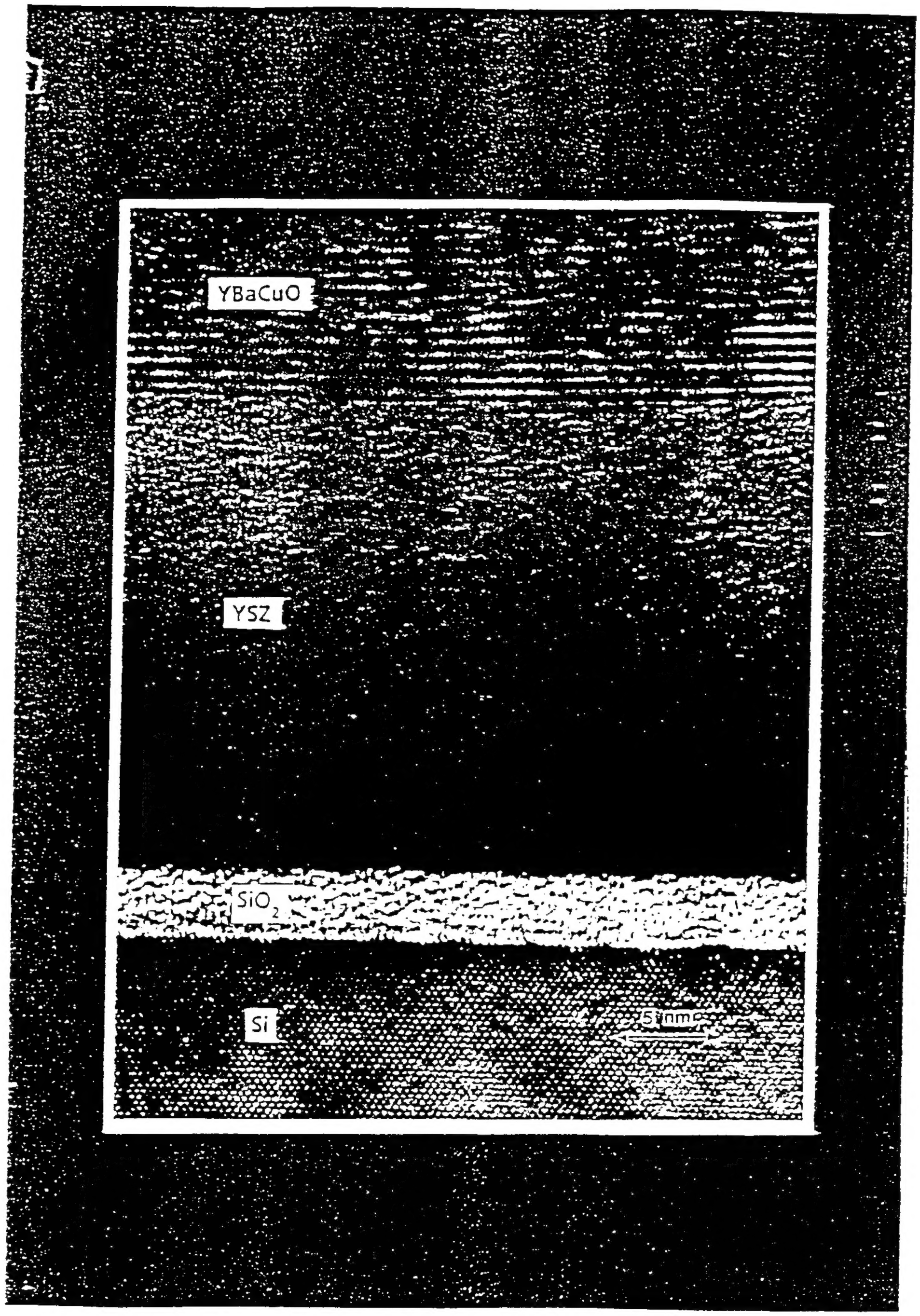

Fig. 1 Cross-section transmission electron micrograph image of YSZ buffered film of YBCO grown on a silicon substrate

3.b. Sample preparation and microbridge uniformity and reproducibility

Samples were prepared by contact optical lithography with the resolution of about 0.5 μm (with the smallest feature 2 μm). The uniformity of the Josephson junctions was tested by measuring electrical properties of 9 junctions connected in series (but with the option of measuring each of the junctions independently). The results on the resistance distribution of these junctions which characterize the uniformity of film and lithography before e-beam writing is presented in Fig.2. and Fig.3. The mean square deviation $\sigma \approx 2\%$ if we don't take into account the first junction (even if we do it is not more than 5%).

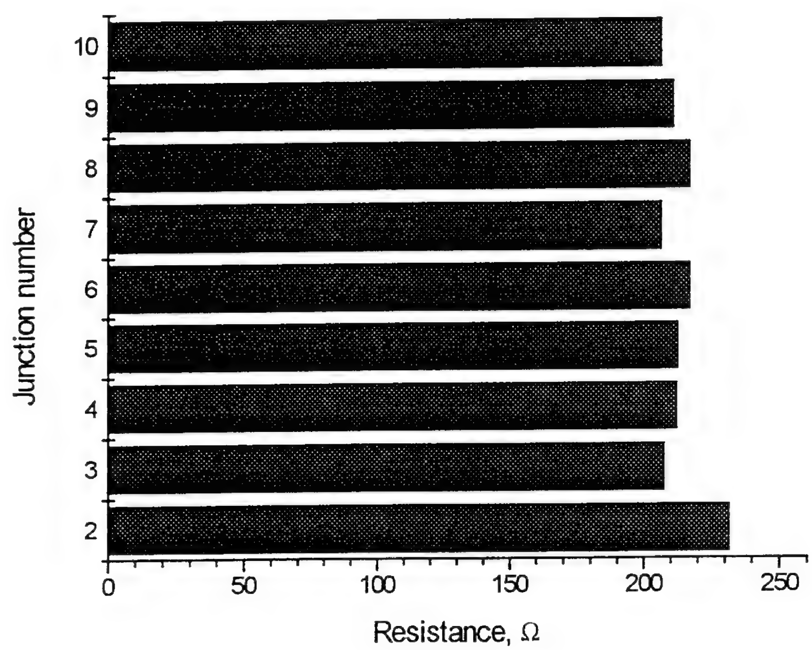

Fig. 2. Histogram of the resistance distribution of the 9 nominally identical junctions before e-beam writing

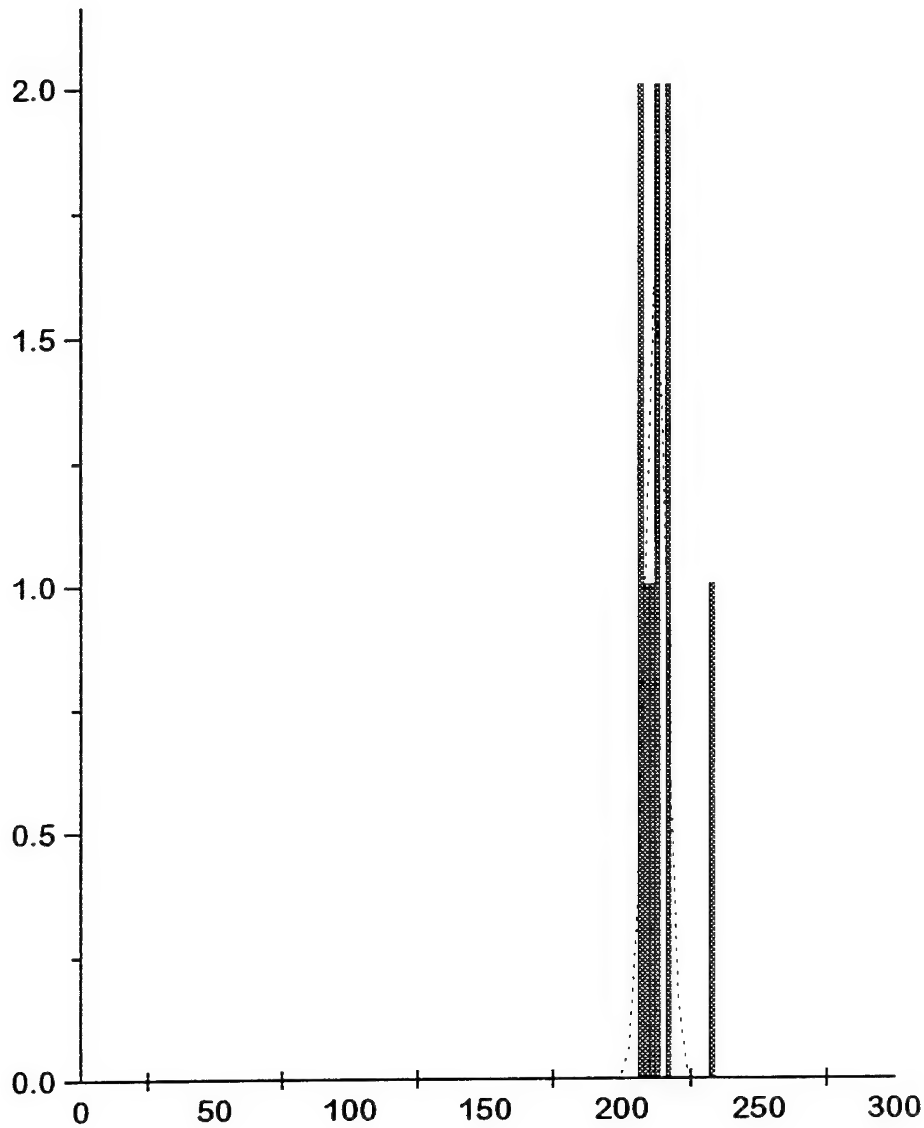

Fig. 3 Gaussian fit to the resistance distribution for the junctions in Fig. 2: Average resistance <R> =212.5 Ohm; mean square deviation σ~3.8 Ohm (less than 2%).

4. RSFQ Flip-Flop

4.a. Operation of the RSFQ Flip-Flop:

Our circuit (Fig. 4a) is nominally symmetric and includes two DC/SFQ converters (using Josephson junctions *J1L, J2L* and *J1R, J2R*), two Josephson transmission lines (*J2L-J4L* and *J2R-J4R*), RS SFQ flip-flop [1] (*J5L, J6L* and *J5R, J6R*) and readout SQUID (SFQ/DC converter, junctions *J7L* and *J7R*). If the inductive parameter $\beta_L = 2\pi I_C L/\Phi_O$ of the flip-flop (where I_C is the effective critical current of junctions *J6*, while L is the total inductance of the loop) is larger than 1, the loop can have several stable flux states – see, for example, Ref. 5. Switching between the neighboring states which differ by a single quantum of magnetic flux trapped in the loop (i.e., setting and resetting the flip-flop) may be achieved by sending an SFQ pulse along the appropriate Josephson transmission line (JTL) biased by dc currents I_2-I_4. The pulse may be generated by junction *J2* (*L* or *R*) by raising the corresponding external current I_1 above some threshold level I_t. As a result the number of flux quanta in the DC/SFQ converter loop (inductance L_L or L_R) decreases by one. In order to restore the initial state of the converter, current I_1 should be decreased below another threshold $I_t'' < I_t$, so that a new flux quantum could enter the loop through the junction *J1*. Finally, junctions *J5* (*L* and *R*) guard the flip-flop against stray SFQ input pulses: say, sending one more flux quantum along the left JTL after the flip-flop has already been set, should lead to its fallout from the circuit via junction *J5L*.

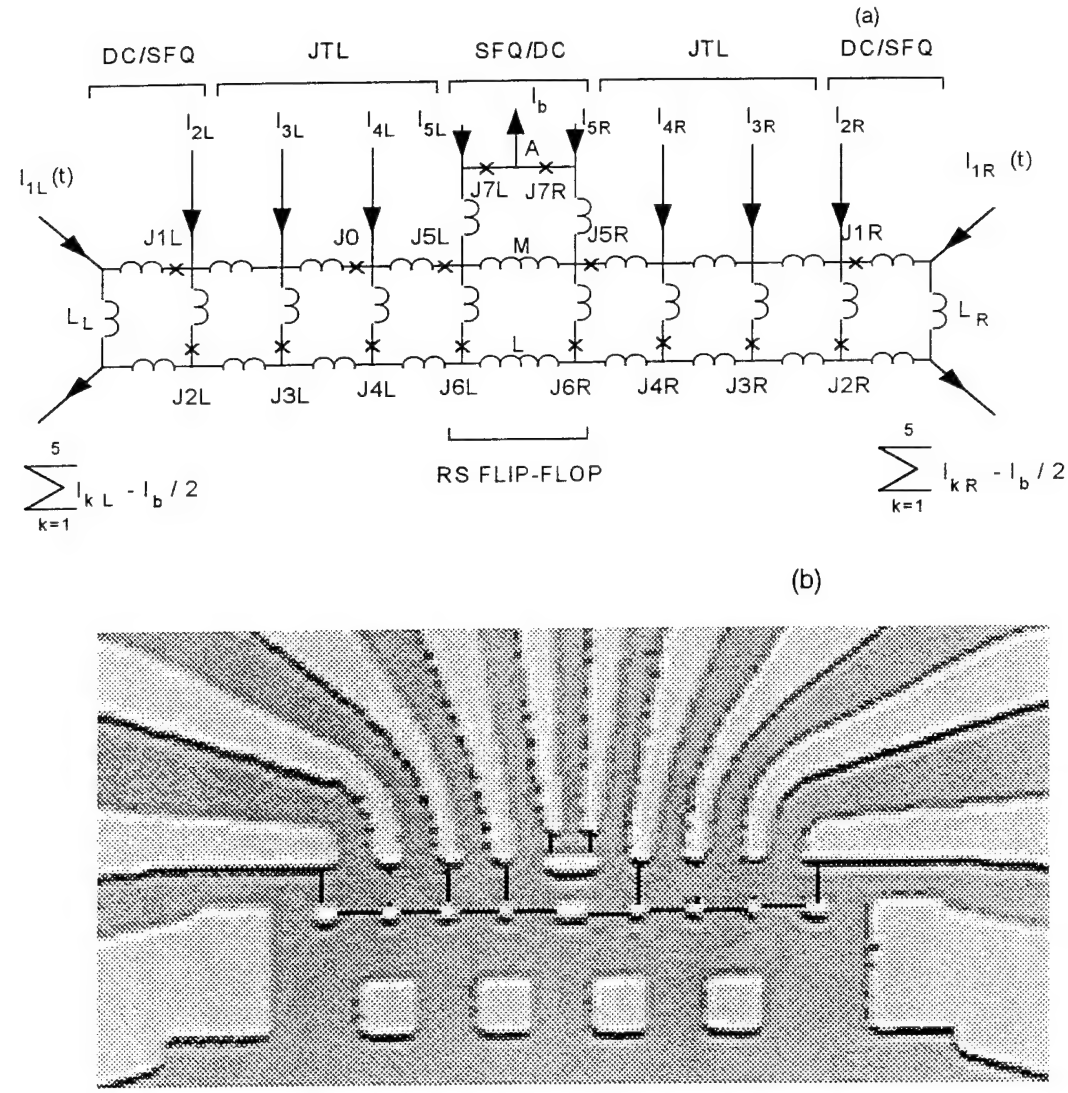

FIG. 4. Single-layer *YBCO* thin-film circuit consisting of two DC/SFQ converters, two Josephson transmission lines (JTL), SFQ RS flip-flop, and an SFQ/DC converter: (a) - equivalent circuit; (b) - micrograph of the fabricated sample. Hand-drawn thin lines mark locations of the Josephson junctions. Junction *J0* was formed by mistake, and does not affect substantially the circuit operation.

Switching of the flip-flop can be monitored by measuring the dc voltage V_{out} across the read-out SQUID (terminal A in Fig.4a), provided that the dc bias current I_b is above

the critical current $I_c \approx I_{7L} + I_{7R}$ of the SQUID. The SQUID may be tuned to a bias point with high transfer factor $\eta = |dV/d\Phi_x|$ by a proper choice of both I_b and the differential current $I_H = I_{5L} - I_{5R}$ which changes the magnetic bias Φ_x applied to the SQUID loop.

4.b. Circuit fabrication

4.b.1. Optical lithography.

The circuit has been fabricated using a $c_\perp$ $YBa_2Cu_3O_{7-x}$ film of thickness d=50 nm which was grown on $LaAlO_3$ substrate by the BaF_2 process [6]. The film was then patterned (see micrograph in Fig. 4b) by optical lithography using PMMA resist and etched in 0.01% water solution of HNO_3.

4.b.2. Electron-beam writing and measutrement setup

Josephson junctions were formed by direct e-beam writing using a scanning electron microscope (Philips CM-12) [7]. The electron irradiation dose per unit length ~ 0.5 C/m was chosen to provide the effective critical temperature of the junctions close to 30 K [7]. The 5x5-mm^2 sample was mounted onto a holder providing reliable pressure contacts between the gold-plated beryllium-bronze springs and 100 nm-thick gold contact pads deposited on the $YBa_2Cu_3O_{7-x}$ film. During the measurements the holder was placed above the liquid helium surface in a storage dewar, and the temperature was controlled with stability better than 0.03 K.

4.c. Low-frequency testing

Low-frequency testing was carried out using a multi-channel data acquisition system controlled by OCTOPUS software [8]. For quantitative testing of the circuit, the dc currents biasing the JTLs (I_2-I_4) and the flip-flop (I_5) were fixed slightly below their critical values, and the output voltage V_{out} was recorded as a function of currents I_{1L} and I_{1R}. In order to cancel linear crosstalk effects, the magnetic bias I_H of the SQUID was changed simultaneously according to $\delta I_H = \alpha I_{1L} + \beta I_{1R}$, where α, β are small (~0.03) emperically found factors.

5. Experimental results

Figure 5 shows a typical result of such an experiment at T=26.0 K. Increase of I_{1L} beyond the threshold $I_{tL} \approx 0.4$ mA leads to a jump of V_{out}, manifesting the change in the flux state of the flip-flop. If now I_{1L} is decreased to zero and increased again, no substantial change of V_{out} will result. However, if a similar pulse of I_{1R} with an amplitude above $I_{tR} \approx$ 0.55 mA is applied before the next cycle of I_{1L}, the output voltage returns back to the initial value as it should [1-3]. The results of this experiment are presented in the time domain in the right part of Fig.6 (single pulse pattern). The left part of this figure (double pulse pattern) shows that application of the second current pulse to the same input of the flip-flop does not change its state, in agreement with the concept of the circuit operation.

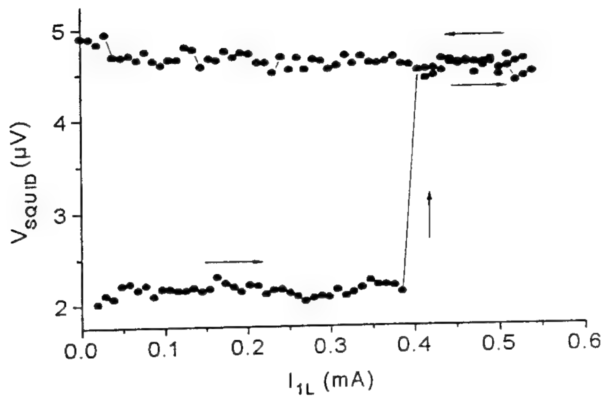

Fig. 5. Readout SQUID voltage V_{out} as a function of current I_{1L} (for explanations, see the text). T=26K, I_{2L}=0.2 mA, I_{3L}=0.11 mA, I_{4L}=0.125 mA, I_{5L}=0.17 mA, I_{5R}=0, I_{2R}=0.35 mA, I_{3R}=0.33 mA, I_{4R}=0.22 mA, I_b=0.07 mA.

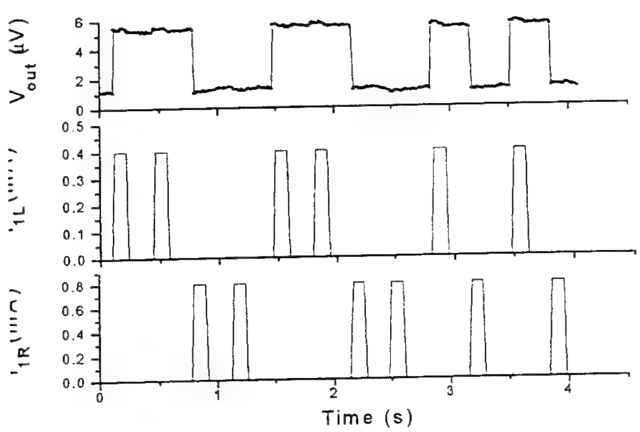

Fig. 6. Operation of the system, presented in the time domain (for the same parameters as in Fig. 2). Results were essentially the same within ± 10% margins for I_2, I_3, I_4 .

These results, however, cannot serve as the final proof of the correct operation of the system. One could argue, for example, that the flip-flop was switched directly by external currents I_1 sneaking along the superconducting electrodes of the JTLs to junctions *J6*. In order to exclude alternative interpretations such as this, we have carried out numerous additional measurements together with numerical modeling of the system using PSCAN software [9].

Critical currents I_C of the junctions used in the simulation were evaluated from a simple model taking into account progressive annealing of the sequentially fabricated e-beam junctions at room temperature (the process of writing 15 junctions took about 8 hours). From the known time lag between e-beam writing of each junction and cooling the sample below T_d, where $T_d \approx 250$ K is the temperature at which the annealing practically stops, we found their effective critical temperatures and hence critical currents at operation temperature. These calculated values of I_C (at T=26 K they ranged from 0.08 to 0.35 mA) have been found to be in fair (~15%) agreement with the experimental critical currents of all parallel groups of junctions (like J1L, J2L, J3L, and J15) which could be measured. The only noticeable exception were the readout SQUID junctions J7L and J7R, nominally 2μm-wide (width of all other junctions was 4 μm). Real critical currents of these two junctions (~0.035 mA) were about twice as small as the calculated values, apparently indicating a substantial (~1 μm) undercut of the thin film edges.

Inductances of the superconducting loops were estimated from the independently measured effective penetration depth $\lambda_\perp = \lambda^2/d$ (at T=26 K, $\lambda_\perp = 2.5 \pm 0.5$ μm) and the circuit geometry. For the mutual inductance M between the readout SQUID and the basic circuit this estimate gives ~20 pH, in good agreement with the experimental result (19 pH). For the quantizing loop of the flip-flop the estimate gives inductance $L \approx 25$ pH, for the input inductances $L_L \approx L_R \approx 3$ pH, while the inductance of each JTL mesh is about 12 pH.

Numerical modeling using these values has shown that the circuit should really work as initially intended. Moreover, the calculated switching thresholds $I_{tL} \approx 0.5$ mA, $I_{tR} \approx$ 0.7 mA are in reasonable agreement with the data (see above), considering the approximate character of the inductance estimates. The same can be said of the derivatives

D_i of the thresholds I_t over the JTL bias currents I_i; for example for the left half of the circuit the simulations give D_2= −0.34, D_3= −0.53, and D_4= −0.76, while in the experiment D_2= −0.24, D_3= −0.32, and D_4= −0.62 (see Fig.7). Most importantly $|D_i|$ increases with i; this shows that the farther the current injection point from junction J2 (and hence the closer it is to, say, J6) the weaker the influence of a particular dc bias current on the switching threshold. This result clearly indicates that it is junction J2 (rather than J6) which constitutes the bottleneck of the switching process, and hence the flip-flop is indeed switched by the dynamic SFQ pulses [10].

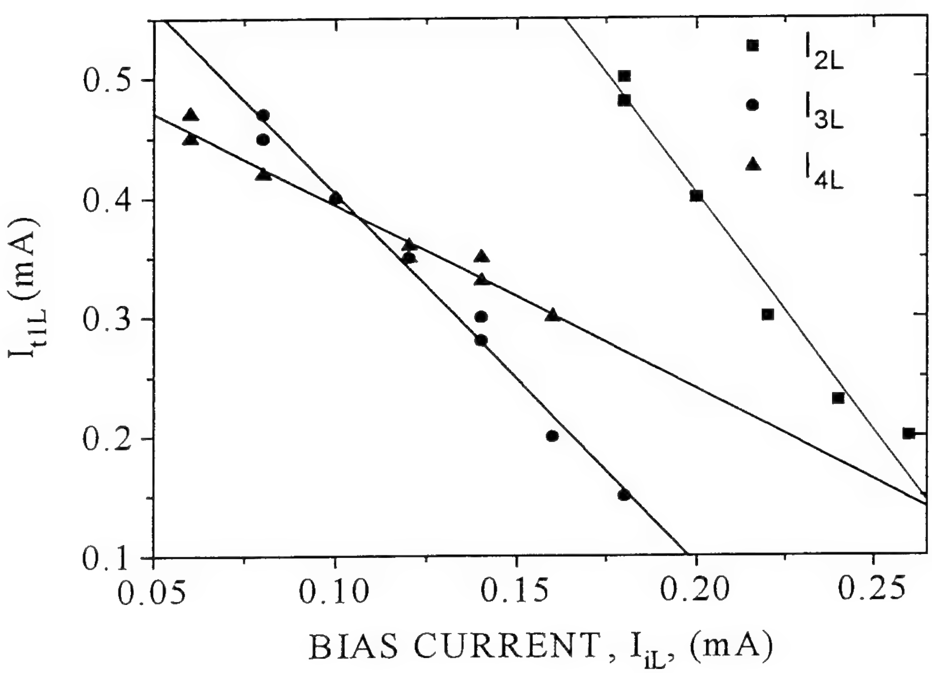

Fig. 7. Threshold current I_{t1L} vs. bias currents I_{iL} for the left part of the circuit.

5. Statistics of switching thresholds and error rates.

Finally, we have measured statistics of switching thresholds I_t, by ramping up the corresponding currents I_1 at a rate ~0.1 mA/s 100 times. The circuit operated *correctly and reliably* (without errors) 100 times out of 100. At 26 K, the statistics could be crudely fitted by the Gaussian distribution (see Fig.8) with the standard deviations $\sigma_L \approx 9$ μA and $\sigma_R \approx 12$ μA for I_{tL} and I_{tR}, respectively. These numbers are to be compared with the estimates $\sigma_L \approx 10 \pm 3$ μA and $\sigma_R \approx 12 \pm 4$ μA, following from the thermal activation theory for the overdamped RSJ-model junctions (see, for example, Eq. (1) in Ref. 11), with the critical currents of junctions *J2L* and *J2R* calculated as discussed above, and the experimental values of the coefficients D_2 [12]. This result shows that the switching statistics is dominated by the equilibrium thermal fluctuations.

7. Summary

To summarize, we have successfully demonstrated operation of a simple all-high-T_c superconductor RSFQ circuit at T~30 K [13]. At these temperatures, thermally-induced r.m.s. fluctuations of the switching thresholds are still considerably smaller than the persistent current $I_p = \Phi_0/L$~70 μA induced by the switching between the neighboring flux states of the flip-flop. For our circuit, increase of temperature to 77 K (while keeping the critical currents at the same level by increasing the critical temperature of the Josephson junctions to about 80 K) would lead to $\lambda_\perp$~4 μm and I_p~60 μA, while fluctuations of the switching thresholds $\sigma \propto T^{2/3}$ would reach ~6 μA (when reduced to one junction). Hence

the circuit could still operate at 77 K, although with a considerable rate of spontaneous switching between its stable states [5]: $\Gamma \sim \omega_c \exp\{-(I_p/\sigma)^{3/2}\} \sim 10^{-1}$ s^{-1}.

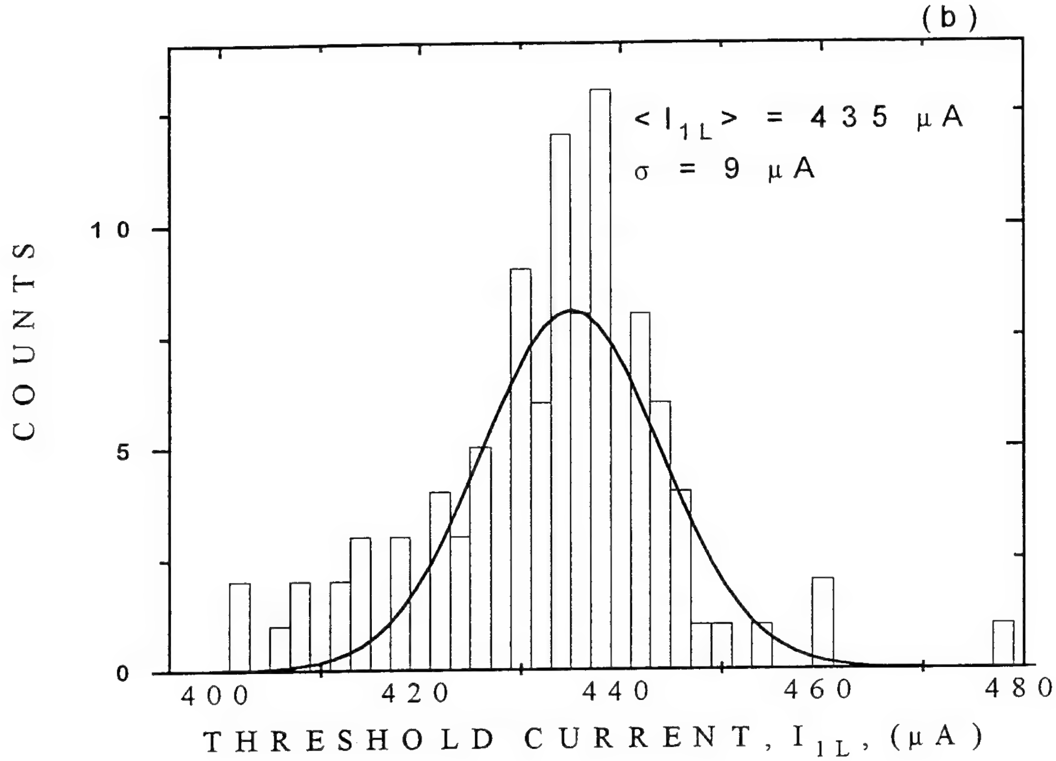

Fig. 8 System switching at $I_{1L}=I_{t1L}$: (a) - a single switching event; (b) - histogram of the switching thresholds fitted by a Gaussian

8. Josephson Junctions and SQUIDs on silicon (brief outline).

We have successfully fabricated and tested High Temperature Superconducting Josephson junction on silicon substrate. The resistance of these junctions were of the order of 1 Ohm, and critical currents over 0.1 mA were obtained. Critical currents were observed up to 77 K. Electron beam modified junctions exhibited microwave-induced Shapiro steps, magnetic interference patterns with strong central maxima. We have also made and studied the first SQUIDs on silicon made by electron beam writing.

8.a. DC characterization and microwave properties.

Fig. 9 shows the R vs T of the SQUID measured before and after e-beam irradiation.

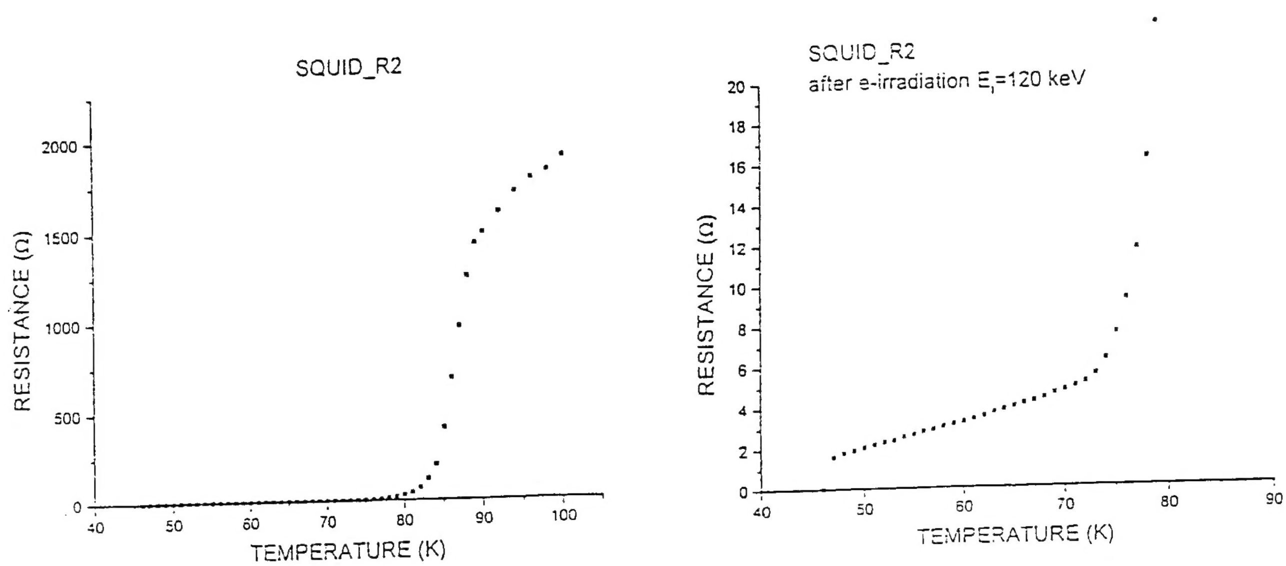

Fig. 9. Resistance vs T curves of an e-beam modified SQUID fabricated on a silicon substrate measured before and after e-beam pattering.

Fig. 10 shows the curve for the SQUID of Fig. 9 at T = 54 K under microwave irradiation. Noise rounded Shapiro steps are clearly visible.

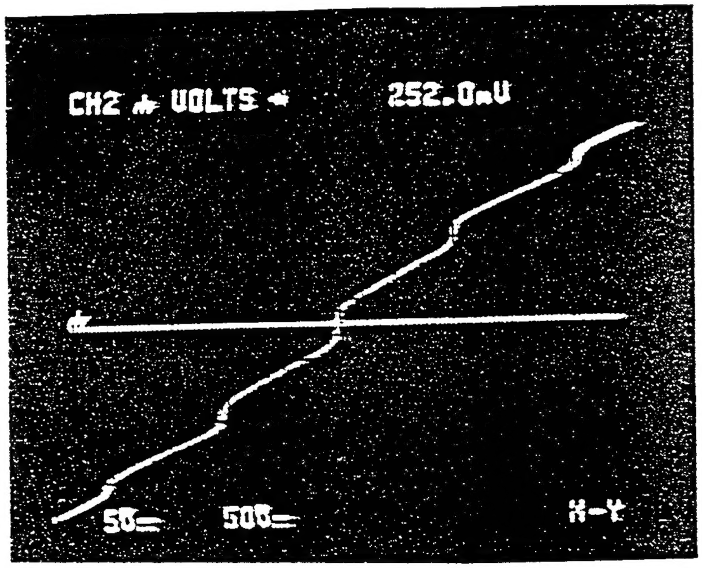

Fig.10. Microwave-induced Shapiro steps in the IV curve of a SQUID on silicon

9. Conclusions and possible future directions

This work demonstrates viability of electron beam writing technique for fabricating HTS RSFQ circuits. It also clearly shows the feasibility of integrating HTS with silicon-based technology using electron-beam writing technique to provide natural interconnect between RSFQ HTS logic and silicon technology.

A further improvement of the reliability, as well as fabrication of more complex high-T_c RSFQ circuits, will require a substantial increase of I_p, via reduction of inductances by using thicker superconducting films and multi-layer circuits.

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[4] To our knowledge, preliminary claims from other groups to successful testing of high-T_C RSFQ circuits have not been confirmed.

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